PLANETESIMALS BORN BIG BY CLUSTERING INSTABILITY?

Jeffrey N. Cuzzi[1], Thomas Hartlep[2], Justin I. Simon[3], and Paul R. Estrada[4]; [1]Ames Research Center, NASA (Mail Stop 245-3, Moffett Field, CA 94035); jeffrey.cuzzi@nasa.gov, [2]thomas.hartlep@nasa.gov, [3]justin.i.simon@nasa.gov, [4]paul.r.estrada@nasa.gov.

Introduction: Roughly 100km diameter primitive bodies (today's asteroids and TNOs; [1]) are thought to be the end product of so-called "primary accretion". They dominated the initial mass function of planetesimals, and precipitated the onset of a subsequent stage, characterized by runaway gravitational effects, which proceeded onwards to planetary mass objects, some of which accreted massive gas envelopes. Asteroids are the parents of primitive meteorites; meteorite data suggest that asteroids initially formed directly from freely-floating nebula particles in the mm-size range.

Unfortunately, the process by which these primary 100km diameter planetesimals formed remains problematic. We review the most diagnostic primitive parent body observations, highlight critical aspects of the nebula context, and describe the issues facing various primary accretion models. We suggest a path forward that combines current scenarios of "turbulent concentration" (TC) and "streaming instabilities" (SI) into a triggered formation process we call *clustering instability* (CI). Under expected conditions of nebula turbulence, the success of these processes at forming terrestrial region (mostly silicate) planetesimals requires growth by sticking into aggregates in the several cm size range, *at least*, which is orders of magnitude more massive than allowed by current growth-by-sticking models using current experimental sticking parameters [2-4]. The situation is not as dire in the ice-rich outer solar system; however, growth outside of the snowline has important effects on growth inside of it [4] *and* at least one aspect of outer solar system planetesimals (high binary fraction) supports some kind of clustering instability [5,6].

Observations: Amongst the most diagnostic meteoritic observations are the several-Myr spread in formation ages [7,8], the apparent rapid accretion of a given body when it did occur [10], several indications that, before their internal heating, primitive 100km bodies were homogeneous thoughout – physically, chemically, and isotopically [11], and evidence both for [12] and against [13,14] radial mixing of initial constituent particles. These observations (and properties of asteroid families [1]) point to gentle and sporadic formation of internally homogeneous, 100km objects directly from fairly small nebula particulates, some of which may have wandered independently for hundreds of millennia since their formation.

Nebula context: The intensity of nebula turbulence is perhaps the most important and least well understood property of the planetesimal formation environment. Consensus on the intensity (the infamous "α" parameter), not to mention its cause, has shifted often over the years, and recent work leads to a lower limit around $\alpha = 10^{-4}$ [15,16]. The most refined incremental-growth-by-sticking models in turbulent nebulae stall out at mm, cm, and m-size "barriers" due to bouncing, fragmentation, and radial drift [18,3]. In the icy outer solar system, growing particles *may* sneak past at least the first set of barriers in the form of ultra-high-porosity "puffballs" [19,20]. However, even if these barriers could be avoided, new barriers loom everywhere at 1-10km size, due to destructive gravitational scattering by large-scale gas density fluctuations in turbulence [21-23]. Meanwhile, ongoing radial drift in the thermally evolving nebula during this extended stage can lead to changes in composition and redistribution of mass, that can affect how, when, where, and of what planetesimals ultimately do form [4].

Leapfrog or instability models: TC and SI are two somewhat different mechanisms that have been proposed to bypass the barriers to incremental growth, both providing a one-stage collapse from a dense, localized clump of small nebula particles straight to 100km planetesimals [24-26,11]. TC has the advantage of triggering planetsimal formation infrequently, allowing it to continue for several Myr. Original TC scenarios which operated on single-chondrule-size particles [25] have been found to be based on incorrect assumptions [27,28]; new results show that the general idea still forms large planetesimals, but particle sizes must start in the cm-dm range [29,30]. SI has the property that either nothing happens at all unless the conditions are right, and if they are, nearly all the local mass becomes planetesimals immediately; that is, it is a true linear instability. The main problem for SI is turbulence; typical growth-limited particle sizes remain too small to settle vertically into sufficiently dense layers for SI to occur, while "lucky", atypically large particles are far too rare to lead to SI. (see [31] for a more in-depth discussion of SI).

Thus both TC and SI are in a similar bind, requiring particles much larger than current growth models are able to produce (mm-size) under current sticking assumptions. The popular "Pebble Accretion" [32,33] scenario is not a solution to *forming* planetesimals because it requires fairly large "seeds" on which to accrete pebbles. If it is to apply at all to planetesimals, it must merely add thin shells on top of already large objects formed some entirely different way, and the observations argue against inhomogeneity with depth.

Clustering Instability: For SI to occur in a nebula with α =10^{-4}, and local cosmic abundance of solids, particles must grow to meter-radius for settling to occur. Particles of such sizes collide at about 30m/sec – an unlikely stable condition for loose aggregates. However, even if particles can only reach cm-dm size, less settled particle layers still exist. In such a turbulent environment, TC can cluster the cm-dm size particles within these dense (but SI-immune) layers into clumps that can, perhaps, make use of the "peloton" physics of the SI to go on to planetesimals. This is the triggered, or nonlinear, instability we call the *Clustering Instability* or CI. It combines the advantage of a slow, rate-limited triggering by TC (only statistically rare volumes achieve sufficiently high concentration) with a second advantage that only moderate growth-by-sticking beyond current model limits is needed – perhaps only to several cms radius. A full, numerical study of the CI remains to be done. TC models which lead to planetesimal Initial Mass Functions (IMFs), make do with simplified analytical thresholds for planetesimal formation, and lack the full feedback contained in 3D numerical models that display SI [26]; however, none of the SI models have included global nebula turbulence, except for [24] which assumed particles that may be too large to be realistic.

Can "particles" grow larger than the best current models say? In the terrestrial planet region, observations suggest that "particles" of cm-dm size must be *aggregates of chondrules*, since all the most primitive chondrites are composed almost entirely of chondrules (with similar size particles of different composition and associated dust). Detailed models of the growth of aggregates of dust-rimmed chondrules found that growth stalled in the mm-radius range due to bouncing [2]. However, one new and intriguing observation suggests that the models may be missing something [34-37]. The primitive Unequilibrated Ordinary Chondrite NWA 5717 shows dark and light "lithologies" or chondrule clusters, several cm across, with different chemical and isotopic properties, that are very hard to attribute to alteration after formation. These lithologies suggest growth by sticking of chondrules, in two distinct regions, into aggregates, followed by turbulent diffusion of these (still small) aggregates into a region where they accreted together. Highly localized parent body aqueous alteration may have occurred if the chondrules in the darker lithology carried water ice in or on their rims, that was absent on/in the lighter-colored aggregates [34-37].

What can explain this more robust growth by sticking than expected? A clue may be found in the properties of Chondritic Porous (CP) Interplanetary Dust Particles (IDPs). The mineral grain monomers in several IDPs have sizes consistent with aerodynamic sorting [38]. Such tiny grains are strongly tied to the gas flow, and it is hard to sort them by aerodynamics using traditional physics. One new piece of physics that might explain this observation is an enhanced collision rate (because of local density enhancement), combined with a lower collision speed (avoiding the bouncing barrier) *for particles with stopping times very close to the eddy time of the smallest (Kolmogorov) eddy in turbulence* [30,39], The same physics could apply to IDP monomers and chondrules, because of their very different nebula environments. If the physics is validated, then monomer sizes including the long-puzzling chondrule size distributions [37,40] can tell us about their nebula gas environment. In addition, it may be that realistic, irregular, size distributions of silicate grains coated with "sticky" refractory organics [41], or even thin icy rims, might contribute to growing larger aggregate particles than previously thought.

Growth of few-cm-size aggregates, in weakly-to-moderately turbulent nebula where both TC and SI-like processes combine to lead to a triggered CI, might allow roughly 100km diameter planetesimals to be "born big" directly, and sporadically, from freely-floating nebula particles [30].

References:

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